Influence of Metro Vehicle Operation on Adjacent High-Speed Railway Bridge Pier

Guohui Cheng, Yao Shan, and Xiangliang Zhou

Abstract The growing scale of the high-speed railway network and that of the metro leads to an increasing number of intersections between these two traffic modes. To ensure the structural safety during the construction process of metro tunnels constructed beneath existing high-speed elevated lines, rows of isolation piles between these two different kinds of traffic infrastructures have been widely utilized. However, the vibration isolation effect of these piles during the metro vehicle operation process is still not well studied. In this paper, a model that accounts for the interaction between structures (i.e., high-speed bridge, isolation piles and metro tunnels) and soil foundations is established by employing a three-dimensional finite element method to investigate the vibration isolation effect of the isolation piles. The influence of different design parameters of isolation piles on the vibration characteristics of the complete system is investigated. Besides, this paper summarizes the law of wave peaks formation in the vibration magnification area. The results show that: (i) For surface, vibration isolation effect is influenced greatly by the spacing and diameter of isolation piles. The vibration isolation effect of the isolation pile is weakened considerably with increasing pile net spacing and is enhanced with increasing pile diameter. (ii) For high-speed bridge pier top, geometric parameters of isolation piles have little effect on the isolation efficiency. (iii) The increase of pile diameter and spacing makes wave peaks appear easily in the vibration magnifications region.

Keywords Vibration isolation · Isolation piles · Finite element

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1 Introduction

The growing scale of the high-speed railway network and that of the metro network leads to an increasing number of intersections between these two traffic modes. In most of these intersection cases, new constructed metro tunnels beneath existing high-speed railroads are dominant, which brings two issues that need to be taken seriously. First of all, tunnel construction will cause deformation of high-speed railway foundation and endanger traffic safety. Secondly, passenger comfort and structural durability of high-speed railway may be affected by the subway vibration during the operation period. In engineering practice, isolation piles between these two different rail infrastructures have been widely utilized and played an important role in infrastructure deformation controlling in the construction process. As a result, the existing design principle of isolation piles is based on the deformation prediction of infrastructures in constructions, no isolation measure for vibration during operation is considered. Two questions present following this situation: (i) is it possible that the isolation plies would also reduce the influence of metro vehicle operation on adjacent high-speed railway bridge pier? If the answer is yes (ii) how to design the isolation piles to ensure not only the deformation control effect on infrastructures in the construction process, but also the vibration isolation effect between these two rail traffic modes in operation process? To answer these questions, the influence of the isolation piles on dynamic interactions between these two different infrastructures and the environmental dynamic response in the operation stage should be studied.

Isolation piles are generally a row of solid cylindrical piles with the same pile spacing, which is also called row piles. Row pile, trench, and continuous wall are different forms of the vibration isolation barrier. In 1968, Woods [1] designed and carried out a series of in situ experiments to study the effect of a trench on vibration isolation. The amplitude attenuation coefficient was proposed as the evaluation index of the isolation efficiency of the barrier.

$$A_{\text{RC}} = \text{Vertical amplitude behind the barrier/Vertical amplitude without barrier}$$
(1)

Although the existence of a trench system can be an effective approach to reduce vibrations, the application of trench was limited by its small depth [2]. Thus, Rechart et al. [3] used low-cost row piles with great applicability as vibration isolation barriers. The follow-up researchers analyzed the influence factors of vibration isolation effect of row piles. The research methods mainly include two categories: (1) analytical method based on wave function expansion method (WFEM), (2) numerical method based on finite element method (FEM), and boundary element method (BEM).

Pao et al. [4] elaborated on the analytical method by a single hole and carried out a lot of numerical analysis that was the beginning of the analytic solution. On this basis, Aviles and Sanchezsesma calculated the vibration isolation of the periodic piles on the two-dimensional (2D) and three-dimensional (3D) level according to

Graf's additive theorem and wave theory [5, 6]. They considered pile spacing affect the efficiency of vibration isolation. After that, scholars analyzed the influence of different sections, materials, and arrangement of piles on the vibration isolation effect [7–12]. Many achievements have been made in the analytical study of isolation pile parameters. However, because of the complexity of wave scattering, the theoretical methods simplified practical engineering. In order to solve the specific engineering problems efficiently and accurately, numerical methods based on FEM and BEM were found. Kattis et al.[13, 14], Kellezi [15], Tsai et al. [16], Xu [17], and Huang et al. [2] analyzed the vibration isolation performance of isolated piles by FEM and BEM method, and the influence of different materials, cross-section forms, and arrangement of the isolated pile on vibration isolation efficiency is studied. For complex engineering, some scholars used the 3D finite element to establish the simulation model. Guo et al. [18] developed a 3D finite element model including isolation piles, soil, and track structure. The vibration isolation efficiency of the isolated pile under the train load is analyzed. In Wang's paper [19], ANSYS software is used to simulate and analyze the periodic layered vibration isolation barrier. Wang investigated the vibration response of the existing building behind the pile row.

In the development of the analytical method, researchers studied the influence of incident waveform, soil parameters, and row pile parameters on the vibration isolation efficiency. The development and application of computer and finite element theory promoted the progress of numerical solutions. Researchers have gradually improved the boundary conditions in the calculation of specific projects, which makes the calculation results more accurate. However, there are still some problems that have not been considered at present: (i) The pile foundation of the bridge has sufficient stiffness and stability. Whether the application of isolation piles can reduce the impact of vibration sources on pile foundation? If so, whether the parameters of isolation piles have the same impact on the effect of vibration isolation as summarized in surface vibration isolation. (ii) What is the formation law of peak value in vibration magnification area and whether it is related to the parameters of the isolation pile?

To answer the above questions, a 3D finite element model including subway tunnels, isolation piles, and pile foundation of the high-speed railway bridge is built in this paper. According to the research results of previous scholars, it can be found that the significant factors affecting the isolation efficiency of single row isolation piles are the net distance between piles and pile diameter, so they are the parameters of isolation piles analyzed in this paper.

Firstly, the influence of isolation pile parameters on the surface isolation efficiency is analyzed through a series of comparative tests. Then, the vibration data in the area behind the isolation pile are extracted to study the relationship between the peak value of the vibration magnification region and pile parameters. Finally, the dynamic response results of the pier top are extracted to analyze vibration isolation efficiency of isolation pile on pile foundation.
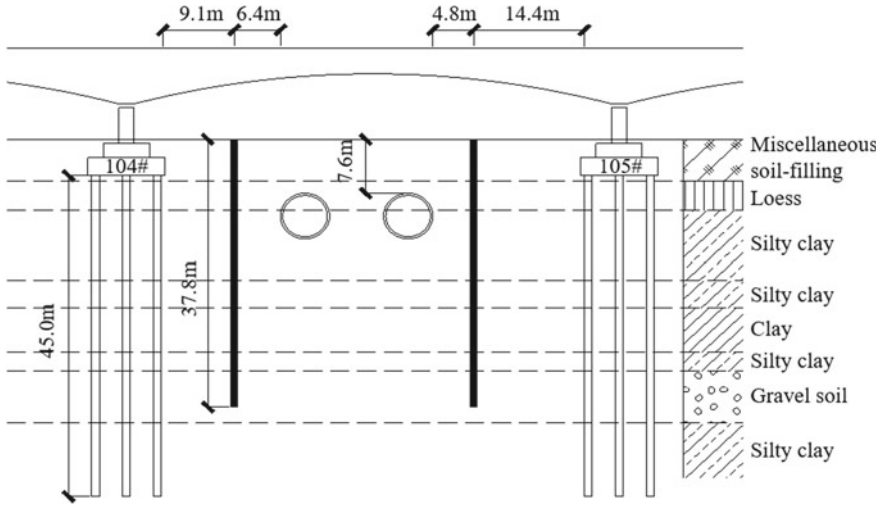
**Fig. 1** Cross-sectional sketch of crossing

2 Background

This paper relies on a project in south China, in which two metro tunnels pass under high-speed railway bridge vertically. The cross-sectional and soil layers of the tunnel are shown in Fig. 1. The buried depth of tunnels is 7.6 m, the outer diameter is 6.4 m, and the inner diameter is 5.8 m. The minimum net distance between the tunnel and the pile foundation is 15.5 m. Bored cast-in-place piles with a diameter of 0.8 m are used for isolation piles on both sides of the tunnel, and the length is 37.8 m. The minimum spacing between the isolation pile and the high-speed railway bridge pile is 9.10 m.

This area is a piedmont alluvial plain landform. The strata exposed in the depth of 60 m are mainly loess, silty clay, and gravel soil, with local sandy soil, and the thickness of Quaternary overburden is more than 50 m. The tunnel is mainly located in loess and silty clay.

3 Numerical Model

3.1 Model Introduction

Limited by the hardware computing capabilities, only a part of the project area can be included in the model. The size of the model should ensure that the calculation results have higher precision while maximizing the calculation efficiency. The calculation results of Lv et al. [20] showed that when the length of the model in the horizontal

Fig. 2 Finite element model
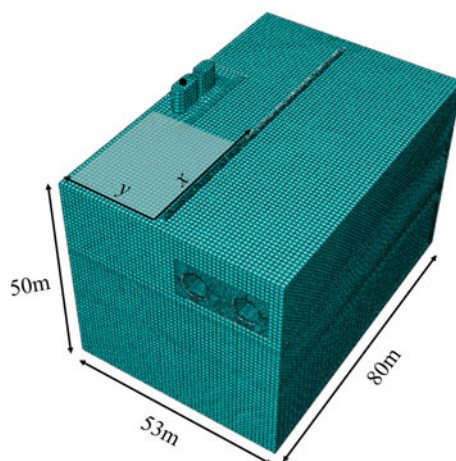
direction is greater than 8 times the diameter of the tunnel, the calculation results can achieve higher precision. Lei [21] claimed that the range affected by subway vibration was within 60 m from the subway line. To guarantee the calculation accuracy, the length, the width, and the height of the model are chosen as 80 m, 53 m, and 50 m, respectively (refer to Fig. 2).

In ABAQUS, elastic waves will be reflected when propagates to the boundary of the model, which cause a great interference to the calculation of the dynamic response, so that the calculation result cannot reflect the real situation. Therefore, boundary conditions need to be specially treated to reduce or eliminate errors caused by model boundaries. Artificial boundary conditions are used to absorption of elastic waves, thereby simulating an infinite boundary. At present, viscoelastic boundary and infinite element boundary are two widely used artificial boundary methods. The model in this article sets the infinite element boundary.

Discretizing the model region into a finite number of meshes in the finite element model causes a low-pass effect, i.e., waves above a certain frequency are truncated in the model. The magnitude of this cutoff frequency depends on the size of the mesh in the model and the minimum shear wavelength considered. In general, for a finite element model using a lumped mass matrix, a higher calculation accuracy can be obtained when the minimum shear wavelength is longer than 6–8 times the unit lengths [22]. In this paper, under the premise of ensuring accuracy, the model mesh is divided into 0.5–1 m hexahedral elements (finite elements: C3D8R, infinite element: CIN3D8). The overall mesh of the model is shown in Fig. 2.

3.2 Material Parameters and Load

In order to improve the calculation efficiency, this paper assumes that the soil is an isotropic homogeneous medium, regardless of the soil microstructure and internal pores, and ignores the initial stress of the soil. Besides, due to the small dynamic strain caused by traffic load, the soil and structure are generally considered to be in the stage of elastic deformation, and the materials in the model are all set to the linear elastic constitutive. According to the on-site geological exploration data, material properties are as follows (The order of soil is the same as Fig. 1) (Table 1).

This paper applies the Rayleigh damping theory to simulate material damping. The theory assumes that the damping matrix of the element is a linear combination of the mass matrix and the stiffness matrix:

$$[C] = \alpha[M] + \beta[K] \tag{2}$$

α and β satisfy the following equation:

$$\xi_n = \frac{\alpha}{4\pi f_n} + \beta\pi f_n \tag{3}$$

where ξ_n is the damping ratio at frequency f_n. The maximum and minimum frequency this paper concern is 50 Hz and 5 Hz, respectively, at which $\xi_n = 0.05$. After calculation, $\alpha = 2.856$, $\beta = 2.894 \times 10^{-4}$.

Table 1 Material properties

Material name	Natural density (kg/m^3)	Dynamic elastic modulus (MPa)	Dynamic Poisson's ratio	Depth
Miscellaneous soil-fill	1900	99	0.432	5.8
Loess	1910	172	0.421	4.2
Silty clay	1940	262	0.411	9.8
Silty clay	1920	606	0.42	3.8
Clay	1940	650	0.39	6.2
Silty clay	1940	1068	0.421	2.7
Gravel soil	2120	1768	0.409	6.3
Silty clay	1940	920	0.41	–
Caps	2500	40,000	0.2	–
High-speed bridge pile	2500	40,000	0.2	–
Shield segment	2500	45,000	0.2	–
Track bed slab	2500	40,000	0.2	–
Isolation pile	2500	40,000	0.2	–

Fig. 3 Fastener force
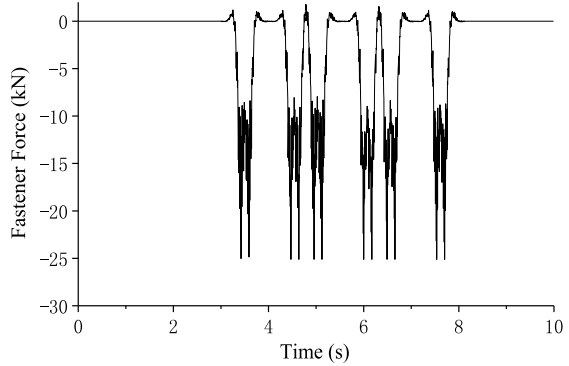
The subway load applied in this paper refers to the track fastener force used in the Si's model [23]. When the subway is running, the fastening force of a fastener on the track is shown in Fig. 3. The phase difference is applied to adjacent fasteners to simulate metro driving.

4 Data Analysis

The data of the measuring point (the black point in Fig. 2) is extracted to represent bridge pier top, and the measuring region (the shadow area Fig. 2) represents the surface near the cap. The x-direction is parallel to the direction of row piles, and the y-direction is perpendicular to it.

For the high-speed bridge pier, the dynamic response evaluation indicator selected is a_z: the maximum vertical acceleration of the pier top. For the surface near the cap, the selection of dynamic response evaluation indicator a'(normalized acceleration amplitude) refers to the amplitude attenuation rate proposed by Wood [1], and the calculation is shown in Eq. 4.

$$a' = \frac{a_{max}}{a_{0-max}} \tag{4}$$

where a_{max} is the maximum value of the vertical acceleration at a point in the presence of the piles;a_{0-max} is the maximum value of the vertical acceleration at the same point in the absence of the piles. The other parameters used in this paper are:

d: diameter of isolation pile;

l: piles spacing;

l^*: net spacing of piles ($l^* = l - d$).

The geometrical parameters of piles considered in this work are the diameter d and the net spacing l^*. It is noted that when one parameter is investigated, the other parameters are kept constant. Ding et al. [10] found that: if the spacing of

Table 2 Parameters of isolation piles

Situation	d(m)	l(m)	l^*(m)
Case 1	0.8	1.2	0.4
Case 2	0.8	1.6	0.8
Case 3	0.8	2.4	1.6
Case 4	0.8	3.2	2.4
Case 5	0.4	2.0	1.6
Case 6	0.6	2.2	1.6
Case 7	0.8	2.4	1.6
Case 8	1.0	2.6	1.6

isolation piles is not more than four times the diameter of piles, it could ensure good screening effectiveness. Therefore, considering the construction situation, the different situations are summarized in Table 2. Case 1–4 are used to analyze the influence of net spacing on vibration isolation efficiency, Case 5–8 focus on the diameter.

4.1 Vibration Response of Surface

Figure 4 displays the vibration of normalized acceleration amplitude of surface under different net spacing and diameters. It shows that there are vibration magnifications near the isolation pile, which is caused by the scattering of elastic waves between the isolation piles. The wave trough behind the vibration magnification region represents the optimal attenuation region. Figure 4a shows that with the increase of pile spacing, the vibration attenuation decreases. As shown in Fig. 4b, the vibration isolation effect of the isolation pile is enhanced with increasing pile diameter. These laws are in
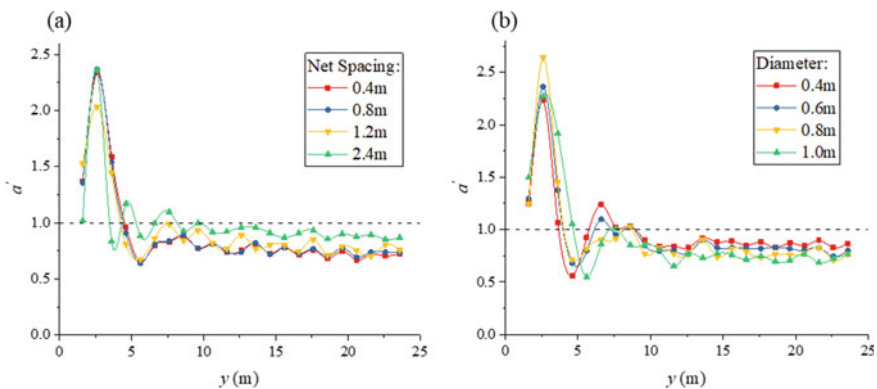

Fig. 4 Normalized acceleration amplitude of surface. **a** $d = 0.8$ m; **b** $l^* = 1.6$ m

conformity with those of the existing theoretical solutions [6, 7, 10]. It is because that when the spacing of piles is large or the diameter of piles is small, the barrier behaves like a set of independent piles instead of a unit. Besides, according to Fig. 4a, it can be found that the attenuation efficiencies of isolation piles are very close when the pile spacing is 0.8 and 0.4 m, which means that keeping the pile spacing 0.8 m is enough to achieve a high isolation effect.

Figures 5 and 6 are the overall vibration attenuation under different pile spacing and pile diameter. Figure 5 shows that when the net spacing of isolation piles increases from 0.4 m to 2.4 m, more peaks appear in the vibration magnifications region and show strong periodicity in the x-direction. That is because piles are separated so far enough that they perform like a set of independent obstacles. Figure 6 shows that there is a similar relationship between the wave crest and pile diameter in vibration magnifications region, and the increase of pile diameter leads to the appearance of peaks. This is because the increase of pile diameter increases the distance between adjacent pile-free area, which reduces the interference of incident wave and peaks appear.
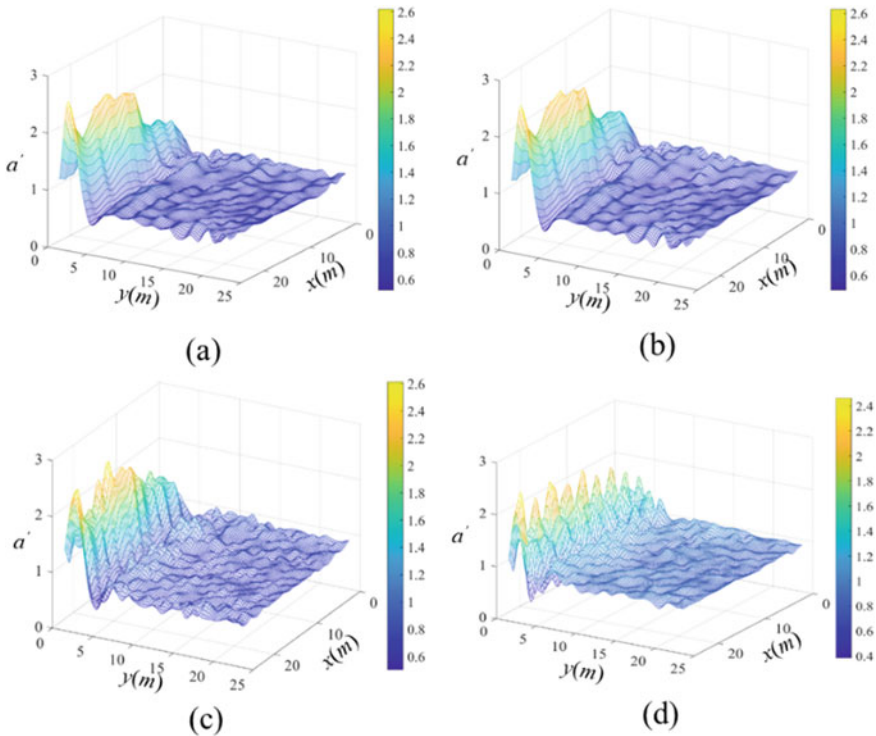

Fig. 5 Three-dimension curved surface of normalized acceleration amplitude under different net spacing. ($d = 0.8$ m). **a** Case 1; **b** Case 2; **c** Case 3; **d** Case 4
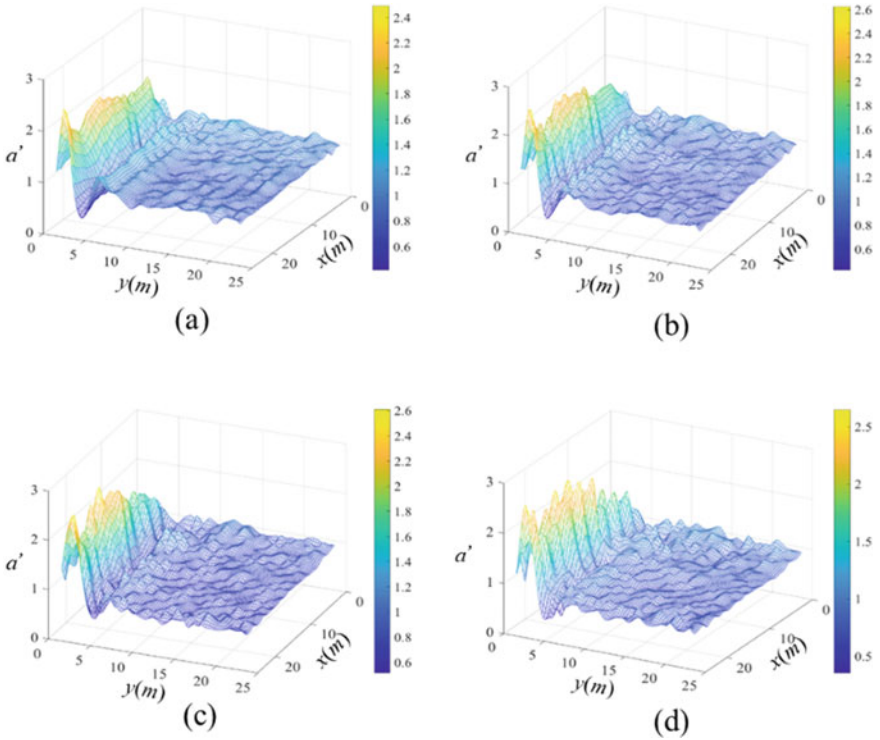
Fig. 6 Three-dimension curved surface of normalized acceleration amplitude under different pile diameters. ($l^* = 1.6$ m). **a** Case 5; **b** Case 6; **c** Case 7; **d** Case 8

4.2 Vibration Response of Pier

The vibration acceleration data of the feature points mentioned above under different spacing and diameter of piles are extracted; Fig. 7 is drawn according to the maximum vertical acceleration in each case.

Figure 7 shows that the isolation pile can effectively reduce the vibration at the top of the pier. Therefore, the utilization of isolation piles between subway and pile foundation building can play a protective role for the latter.

Figure 7a shows that the vibration attenuation increases slightly with the increase of the net distance between piles. Figure 7b shows that the diameter of the pile has no obvious influence on the isolation effect of the isolation pile. Generally, when isolation piles are used to protect the pile foundation buildings, the geometric parameters have little effect on the isolation efficiency.
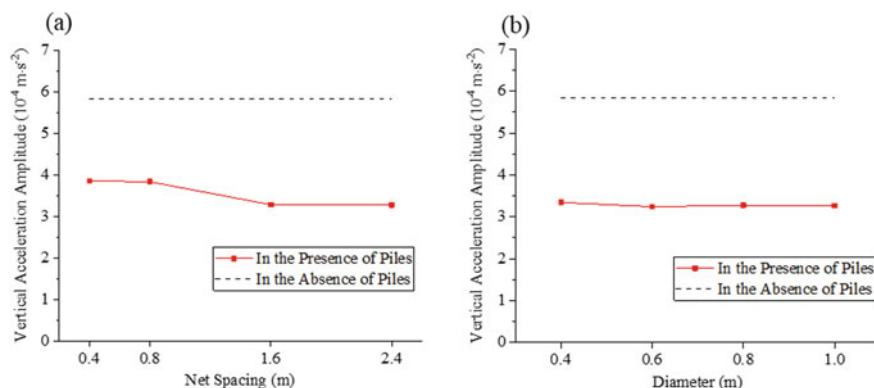
Fig. 7 Vertical vibration amplitude of pier. **a** $d = 0.8$ m; **b** $l^* = 1.6$ m

5   Conclusions and Future Work

Based on the results of the parametric studies of the passive vibration isolation problem considered, which are depicted in Figs. 4, 5, 6, and 7, one can draw the following conclusions:

1. Isolation plies provide vibration isolations between metro tunnels and high-speed railway bridge in the operation stage.
2. For surface vibration, the vibration isolation effect of the isolation pile is weakened considerably with increasing pile net spacing in the range of 0.4–2.4 m and is enhanced with increasing pile diameter in the range of 0.4–1.0 m.
3. Different from the law of ground vibration isolation, for the vibration of the pier top, geometric parameters have little effect on the isolation efficiency.
4. The increase of pile diameter and spacing makes periodic peaks appear easily in the vibration magnifications region.

Our next step is to apply the high-speed rail load on the top of the pier and study the influence of the isolation piles on dynamic interactions between metro and high-speed rail.

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